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Integrated Modeling Framework for Anthropometry and Physiology Virtual Body

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June 2007
Interim Report for April 2006 – May 2007

Air Force Research Laboratory
Human Effectiveness Directorate
Biosciences and Protection Division
Biomechanics Branch
Wright-Patterson AFB OH 45433-7947

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14. ABSTRACT

This paper presents a software framework for visual manipulation and processing of human body anthropometric, skeletal, vascular and other anatomical databases.

15. SUBJECT TERMS

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Integrated Modeling Framework For Anthropometry and Physiology Virtual Body

Patrick Wilkerson and Andrzej Przekwas
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ABSTRACT

We believe that the future of human body testing in military and civilian applications is in using a new generation of "dummies" – "virtual humans". CFDRC's CMB (Computational Medicine and Biology) research group has developed an integrated bioinformatics software framework for intelligent analysis of biomedical databases, generation of geometrical models for simulations, and modeling setup for human biomechanical and physiological performance. The integrated 3D Java based software framework is a fully user-interactive Virtual Body framework for creation and editing the Virtual Body and acting as a front end for multi-scale anthropometry/anatomy physics based simulation software. This paper presents a software framework for visual manipulation and processing of human body anthropometric, skeletal, vascular and other anatomical databases. We have demonstrated the framework for scan/anatomy based virtual human body model generation and predictive simulation of cardiovascular system responses to high-g aircraft maneuvers. The fully developed Virtual Body will allow for complete user control and editing of morphing capabilities of various anatomical systems, including current skeletal and vascular systems, with a framework designed for additional anatomical systems such as muscular, skin, and organs. It provides the capability to generate/edit the static/dynamic human body models from laser scans, anthropometric databases, and other image based anatomical techniques, for predictive modeling of human body performance. The Virtual Body also acts as a data-generator/preprocessor for available human body simulation software including biomechanics, ergonomics, cardiopulmonary physiology, blast injury and other simulators.

INTRODUCTION

The conventional approach for human body performance analysis in ergonomic, apparel, car safety, military performance, de-mining, ballistic protection, and other disciplines is to construct a human "dummy" – a mechanical surrogate of the human body. Nowhere else have dummies gained more popularity and respect than in car crash safety. Mechanical dummies have been also used by the US Air Force Research Laboratory Human Effectiveness Directorate (AFRL/HE) on sled tests replicating pilot emergency ejection events from aircraft cockpits to improve pilot safety [1]. Figure 1 presents classical car crash dummies (HYBRID III and THOR) and a state of the art instrumented thorax for blast explosion testing (HSTM-Johns Hopkins University).

Figure 1. Examples of mechanical dummy models HYBRID III and THOR for car crash safety.

Despite the fact that test dummies have provided invaluable safety data, contributed to vehicle design, and saved millions of lives, they have reached a point of reduced data return as they contain no integrated human physiological systems, capable of only measuring mechanical forces experienced by the dummy. Similar limitations relate to testing on cadavers (good anatomy but no physiology and poor repeatability, i.e. each cadaver is different) and on animal "models" (good physiology, but wrong anatomy and ethical issues). We believe that the future of human body testing in military and civilian applications is in using a new generation of "dummies" – "virtual humans". The work presented in this paper is making a major contribution in that quest, which has been ongoing, with initial emphasis on aviation safety.

For years, modeling and animation of the human being has been an exclusive research goal in computer graphics. Early humans were represented as simple articulated bodies made of segments and joints with a kinematical model to simulate them. But simple skeleton-based models are too limited for realistic human simulation. Recent advances in computer graphics, computing hardware, and bioinformatics have increased the practicality of using computers for multidisciplinary, multi-scale modeling of a human body. The combination of medical imaging, computer graphics, anthropometry, anatomy based image processing, availability of physiological and biological data, and biomedical modeling tools allows for the advancement of predictive tools of functional performance of human beings in various scenarios. The potential in commercial and military applications of human body modeling and bioinformatics software is phenomenal.

Human biology and physiology can be analyzed and simulated using either a "bottom up" approach starting from small scale and building to larger scale (i.e. genome), subcellular structures (organelles), cellular pathways, tissue, organ, organ system, and whole body organism – or in the opposite way by using a "top down" approach. Most of the bioinformatics research follows the former approach, primarily because of the revolution in experimental biology. We believe that there are great scientific, commercial, and military opportunities in establishing a top-down bioinformatics data processing and modeling framework. We envision a bioinformatics framework coupling interfaces to experimental data, data analysis software tools, and multi-scale top-down modeling of the whole-body biomechanics, physiology, and injury. The human body model could be "immersed" in a virtual environment relevant to military and commercial medicine. CFDRC's current Virtual Body software framework is a first step in this direction

3D JAVA BASED VIRTUAL BODY FRAMEWORK

CFDRC has developed an integrated Virtual Body bioinformatics software framework for intelligent analysis of biomedical databases, generation of geometrical models for simulations, modeling setup for human biomechanical and physiological performance, and launching/monitoring such simulations. The developed software is a novel "top-down" multi-scale modeling approach of the human body that allows for integration of systemic, organ, tissue, cellular, and biochemical pathways through the Virtual Body framework and modeling through available CFDRC simulation software.

The Virtual Body framework allows for full 3D generation and editing of anatomical systems such as vasculature and the skeleton. All anatomical systems are mapped to an underlying baseline skeleton framework. Such mapping of the anatomical systems to the baseline skeleton allow for automated morphing of all anatomical systems when the baseline skeleton is moved. In addition, the design of the system allows for future development of additional anatomical systems, including muscles, organs, skin, lymphatics, etc. As well as generation and editing capabilities of the system, the user may import previously saved anatomical systems or system components, to include in the Virtual Body system as desired. Additional file format support is continuously being developed to allow for the importing of system components, such as data extracted from medical images. With full user 3D interactive editing capabilities for all the systems in the Virtual Body, the user is thus able to setup a desired anatomical system for biomechanical and physiological simulations. Such simulations include using CFDRC's CoBi (Computational Biology) software for fully coupled fluid flow, heat transfer, biomechanics, and biochemistry.

Future development of the Virtual body framework will include a component model library of system components, links to anthropometric and biochemistry databases, additional anatomical systems support, and integration to additional biomechanical and physiology/injury simulation software such as AFRL's ATB [2]. Figure 2 illustrates the overall framework of the Virtual Body and related components. Figure 3 illustrates a screen shot of the Virtual Body in it's current state, showing a closed loop human vasculature and baseline skeleton framework in a seated posture. Detailed below are several of the major components of the current Virtual Body framework, followed by an illustrative simulation example.

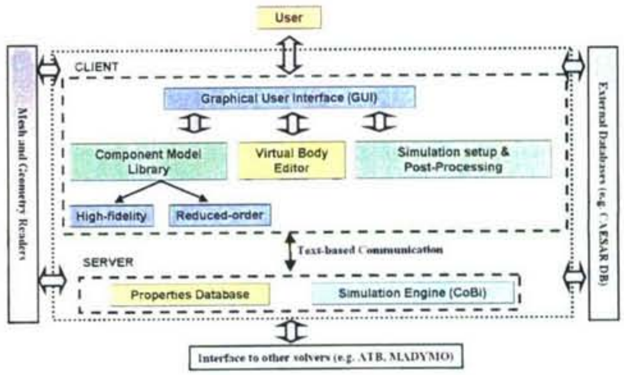


Figure 2. Virtual Body software framework design (current and planned capabilities).

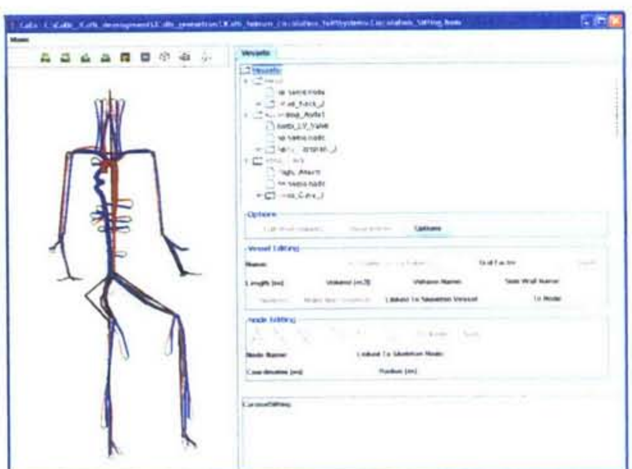


Figure 3. Screenshot of current version of Virtual Body with a skeleton/vascular network in a sitting posture (2D image included for reference).

VASCULAR NETWORK EDITOR

The 3D Java based Virtual Body software enables the user to generate any vascular network desired. The vasculature consists of vessel components, which are in turned composed of node components. The nodes basic definition includes it's 3D spatial coordinates and radius. Groups of nodes therefore make up a vessel, and vessels may be connected to one another through their individual nodes, allowing for creation of a vascular network. Thus, control of the nodes controls the shape, size, and connectivity of the desired vasculature. The generated vasculature is visually represented in the Virtual Body software in two separate ways; (1) a hierarchical tree representation of the vascular network is visualized showing all vessel and node components and their parent/child relationship to one-another, and (2) visualized on the 3D Java canvas which allows for user interactive rotation, translation, and zooming of the complete generated Virtual Body structure via traditional user controlled mouse movements. The 3D canvas and tree representations of the generated vasculature can be seen in the screen shot in Figure 3 with the tree in the upper right hand panel of the screen and the canvas on the left side of the screen.

Full editing capabilities are available of the generated vasculature. Editing can be accomplished by selecting either a vessel or node, by either selecting the component from the tree or interactively selecting the component from the 3D Java Canvas. Once selected, details of the vessel or node component may be edited by the user. Such editing capabilities include, but are not limited to; changing coordinates, radius, parent/child connectivity, grid resolution (for when grid generated), mapping to skeleton baseline (detailed later in paper), visibility/pickability on Canvas, color, etc. Additional editing capabilities for generated vasculature are available, such as scaling and rotation of individual components or the entire geometry. Such editing control by the user allows for very simple or very complex vascular networks to be generated as desired. The full connectivity of the vessels also allows for closed loop vascular networks and/or connectivity points to other components, such as compartmental models in simulation software. Figure 4 illustrates a closed loop vascular network of the human body, showing the arterial network, venous network, and combined arterial/venous closed loop network (with zoomed in view).

In addition, when a node is selected by the user, clicking on (left mouse click) and holding the node in the canvas allows the user to move the node on the canvas by simply moving the mouse as desired. The selected node is moved and relative movement of that node's vessel and all children vessels below are translated accordingly. More detailed movement control (if desired) can be accomplished by first selecting nodes (right mouse click) on either side of the desired node to be fixed in place. Then translation of the selected node and it's relative motion of neighboring nodes will be limited between any selected fixed nodes. This allows for large control of moving nodes on the canvas manually.

Once a vasculature has been generated, either from user generated vessels or imported vasculature extracted from medical imagery, it may be saved and reopened at a later date. Whenever the generated Virtual Body geometry is saved, a 1D wire grid mesh is generated and saved which can be used for simulations with CFDRC's CoBi simulation software. Finally, a critical component of the vasculature generation capabilities described above, is the ability for additional anatomical systems to be easily generated in the same way. Anatomical systems such as muscles, tendons/ligaments, bones, digestive tract, lymphatics, nerves, etc. can be generated and edited in the same manner.

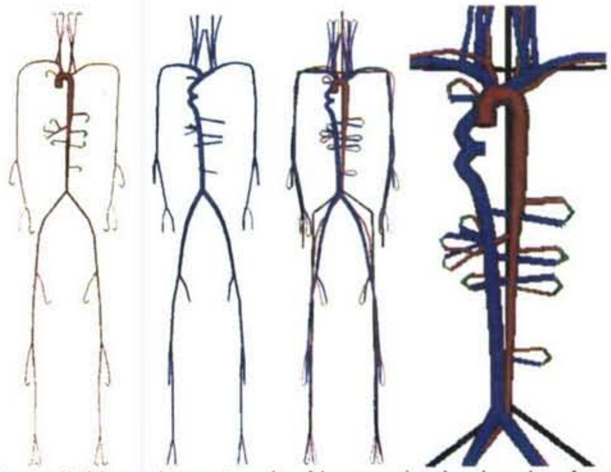
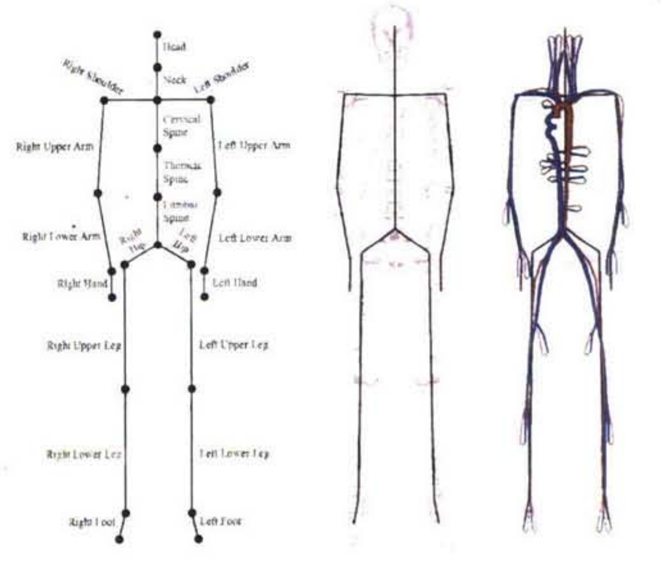


Figure 4. Vascular network of human body showing from left to right: arterial network, venous network, combined closed/loop arterial/venous network, and zoomed in view of closed arterial/venous network.

BASELINE SKELETON FRAMEWORK

A 3D baseline skeletal model was generated to provide an under-lying "backbone" for the virtual human model simulations. This baseline skeleton model is built from the vessel/node elements, therefore it is capable of being scaled and manipulated (re-positioned) as desired by the user in the 3D environment. In addition, the most important capability of the baseline skeletal model is that it can can be mapped/linked to by the vascular network, as well as other user developed anatomical systems.

The developed baseline skeletal model consists of 21 segments, consiting of two nodes apiece. The segments are joined at locations representing the physical joints of the human body. These 21 segments allow for unlimited movement and re-positioning of the virtual human model. The developed baseline skeletal framework serves as the underlying framework of the virtual human generated. The baseline skeletal framework and vascular network (as well as other developed anatomical systems) can be mapped/linked together (described later in paper), allowing for scaling and deforming of the virtual body as desired by the user by simply manipulating the baseline skeletal framework as described in the vascular network editor above. Figure 5a illustrates a schematic of the 21 segment CFDRC designed baseline skeletal model (shown on top of a skeletal surface model, for reference). Figure 5b illustrates an image taken from CFDRC's Virtual Body editor with the developed baseline skeleton framework overlayed on a skeleton image, while Figure 5c shows the same baseline skeleton framework along with a closed loop arterial-venous vascular network. As seen in Figure 5 and Figure 3 (previously), 2D images may also be imported into the Virtual Body editor for reference. If a 2D image has been imported, the image may be selected (or de-selected) by the user in the GUI. Once selected, when the user clicks on a node and begins translation, the node will be able to freely move two-dimensionally, parallel with the image plane (i.e. the node does not have to be in the image plane, it is just forced to translate in a plane parallel with the selected image/plane). The selected node is projected onto the 2D image as a reference for the user. This is especially helpfull when translating 3D geometries which are not in the 2D image plane, and the user wants to move the selected node following a portion of the reference imported image.



(a) (b) (c)

Figure 5. (a) CFDRC developed 3D baseline skeletal model shown in standing posture; (b) 3D baseline skeletal model in Virtual Body; (c) 3D baseline skeleton and closed-loop arterial/venous vascular network in Virtual Body.

LINKING/MAPPING VASCULATURE TO SKELETON FRAMEWORK

A 3D baseline skeleton framework was developed and integrated into the Virtual Body Editor. The purpose of the baseline skeleton framework is schematically illustrated in Figure 6. The skeleton framework serves as the 'backbone' of all other anatomical systems, such as the vascular network or other developed systems (bones, skin, organs, muscles, etc.) which are included in the developed geometry. It can serve as the backbone because all other elements in the geometry will be mapped/linked to a specific skeleton segment. As Figure 6 illustrates, a vascular network can be mapped to the baseline skeleton framework, and then the entire combined system can be scaleable and deformable by simply editing/morphing the baseline skeleton framework in 3D.

The linking/mapping of the vascular system (or other anatomical systems) to the baseline skeleton framework is handled by identifying each vascular vessel's corresponding baseline skeleton segment. This is done when creating (or later editing) each vascular vessel. The actual mapping/linking of the two systems is then handled automatically by the Virtual Body software, determining the closest skeleton node on the linked skeleton segment for each node of every vessel. Automatically determining which skeleton segment each vessel should be linked to was initially attempted, so as to remove any human involvement, but no algorithm could be developed to prevent vessels from one part of the body (i.e. hand) being linked to skeleton vessels from another segment (i.e. upper leg). By specifying which baseline skeleton segment each vessel is linked with, this problem was overcome. With linking/mapping of the anatomical systems to the baseline skeletal framework, automated morphing of the anatomical systems can be accomplished by simply moving the underlying baseline skeleton framework. The technique for such morphing is detailed below.

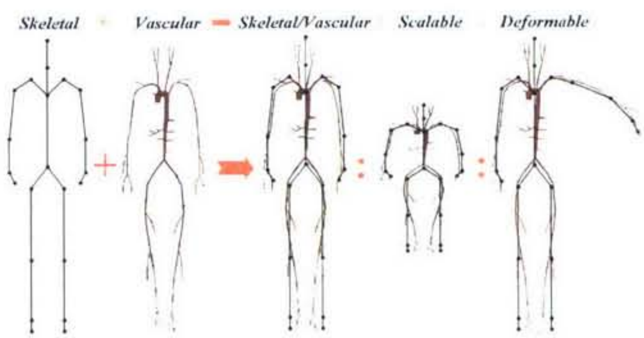
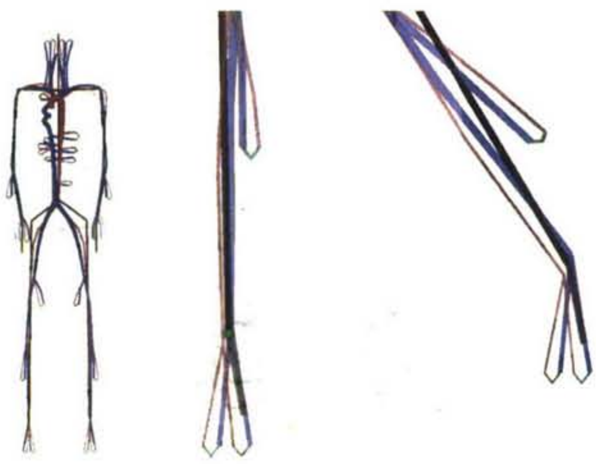


Figure 6. Schematic representation of baseline skeleton framework mapped to vascular network, allowing for scalability and deformability.

AUTOMATED MOVING/MORPHING OF VASCULATURE LINKED TO SKELETON FRAMEWORK

Mapping/linking of the vascular system to the baseline skeleton framework was described in the previous section. The purpose of such a linking system is to allow morphing of the overall system through morphing of the skeleton framework alone. Specifically, if the user wants to morph a standing soldier to a sitting position, simply moving the skeleton arms and legs would be much more efficient than moving all arteries, veins, capillaries, organs, etc. along with the skeletal segments. Through the linking process and the Virtual Body's editing capabilities, such as moving nodes and vessels, this process has been accomplished. Figure 7 illustrates such a process, with Figure 7a showing a full skeleton/vascular network of a standing soldier. Figure 7b is a zoomed in view of the geometries left lower leg. Note that the last node of the lower leg has been selected (green ball). Rotating this node 30 degrees counter-clockwise (translation would work as well) results in the skeleton framework moving along with the linked vascular vessels and nodes, as seen in Figure 7c.

The morphing capabilities illustrated in Figure 7 show the basic principles and capabilities that have been built into the Virtual Body Editor. Improvements still need to be made to handle more accurate real-world morphing. For instance, if a user wants to rotate the lower arm 90 degrees, the lower arm and its linked vasculature will morph fairly accurately. But, the attached hand to the lower arm will simply be translated along with the hand, not rotating itself as well, thus leaving the hand and its linked vessels positioned awkwardly. Another issue is that the linked vasculature is morphed by translating nodes of the vasculature along with the morphing skeleton framework, which may not keep all nodes relative positions with the framework with which it is linked. Issues such as these can currently be handled by then morphing the hand or linked vessels, but could be handled automatically with more sophisticated morphing capabilities in the future. Such issues are currently being addressed. Further, the morphing of the baseline skeleton framework is currently not limited in any way, i.e. no constraints on how the body can be manipulated. Thus, currently the body can be manipulated into configurations which are not realistic (i.e. elbow or knee bending backwards). Work in the coming year will introduce joint restraints to limit manipulation of of the framework to desired human joint limitations.



(a) (b) (c)

Figure 7. (a) Full body model; (b) Left lower leg before and (c) after rotation (2D skeletal image for reference).

Figure 8 illustrates these linking/mapped morphing capabilities by looking at two different postures of a soldier (obtained from 3D laser body scans). A standing soldier vasculature was developed first in the Virtual Body software to mimic the standing posture. Then the sitting soldier posture vasculature was generated by morphing/deforming the generated standing vasculature.

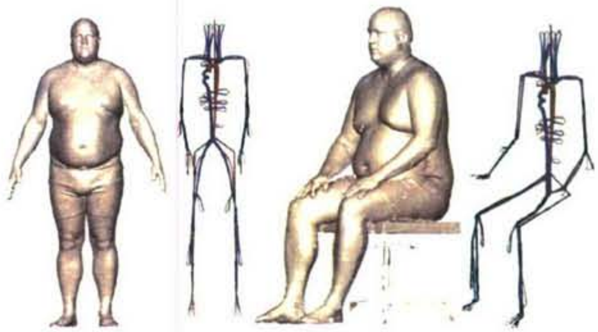


Figure 8. Example generated Virtual Body vasculature (mapped to baseline skeleton framework) of standing body posture and resulting Virtual Body morphed/deformed vasculature. Full body scans from the CAESAR Database [3].

ADDITIONAL ANATOMICAL SYSTEM SUPPORT

As described previously, the Virtual Body software has been designed to handle various anatomical systems, such that they can be defined in segments (vessels and nodes). One such example would be 3D surface models of the body, i.e. CAESAR database [3,4] and the human skeleton. Such skeleton surface models are available, such as the BEL (Biomechanics European Laboratory) [5] database. Figure 9 illustrates this 101 segment human skeleton bone database. The bones can be converted to STL (Stereolithography) file format [6] and imported into the Virtual Body framework using the STL file import capabilities present. Additional file format importers are present and planned in the future.

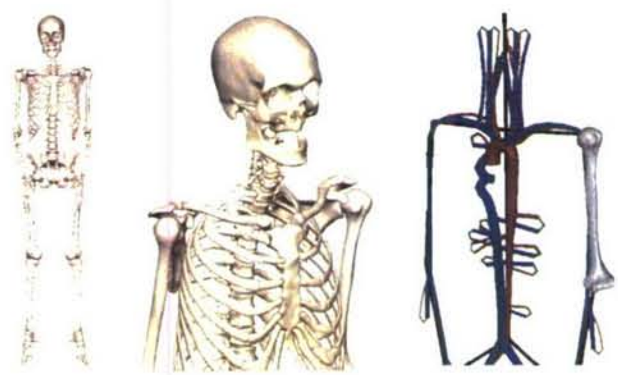


Figure 9. Illustrative snapshots of BEL detailed 101 bone skeletal surface image database and single bone imported to Virtual Body software framework.

Additional anatomical systems which could be generated/imported could be (but not limited to): organs (lungs, liver, kidneys, digestive tract, etc.), muscles, ligament/tendons, nerves, and skin. Each of these systems could be linked to the underlying baseline skeleton framework and morphed as desired by the user. Advanced morphing capabilities will need to be completed to maintain relative positions of such systems as organs and the skin, but such technologies are under development at both CFDRC and other research facilities. Integration of these capabilities is currently underway and presents exciting capabilities for the developed Virtual Body framework.

SIMULATION EXAMPLES

Following are several examples of simulations conducted using Virtual Body generated closed loop vasculature geometries. These simulations were conducted utilizing the Virtual Body for geometry and mesh generation, simulation setup (boundary/volume/initial conditions, solver settings, etc.) and CFDRC's CoBi (Computational Biology) solver was used (solving fluid flow in the vessels, fully integrated cardiopulmonary compartmental model, and elastic vasculature tissue walls).

CLOSED LOOP ARTERIAL/VENOUS CIRCULATORY SIMULATIONS

Utilizing the Virtual Body Editor, a full closed loop arterial/venous circulatory simulation was generated. The simulation included a cardiopulmonary heart/lung compartmental model, an arterial vessel tree starting from the exit of the left ventricle from the heart, a venous tree returning flow to the right atrium of the heart, and capillary vessels connecting the arterial and venous trees. After generating the circulatory vessel structure in the Virtual Body, the file was saved and the wiregrid mesh was automatically generated. Transient simulations using CFDRC's CoBi simulation software were conducted with a heart beat of 75bpm, driving the pulsatile blood flow through the elastic vasculature. The results from the standing soldier simulation qualitatively agreed with anticipated results. Figure 10a illustrates the closed loop vasculature, 10b the generated mesh (zoomed in for viewing), and 10c the resulting pressure distribution in the vasculature at a given instant in time of the pulsatile simulation without and with gravity.

CIRCULATORY SIMULATION OF SOLDIER: SLED TEST ACCELERATION

A circulatory simulation utilizing sled test acceleration data from AFRL's Biodynamic Database [7] was conducted. The data was obtained from the BDB database, test case HIA0921 (Horizontal Impulse Accelerator). The simulation conducted consisted of a soldier in the sitting position, subject to sled acceleration data from the BDB database. Before running simulations with the applied BDB HIA accelerations, the standard geometry was simulated with and without gravity, to insure the mesh was adequate and the simulation with

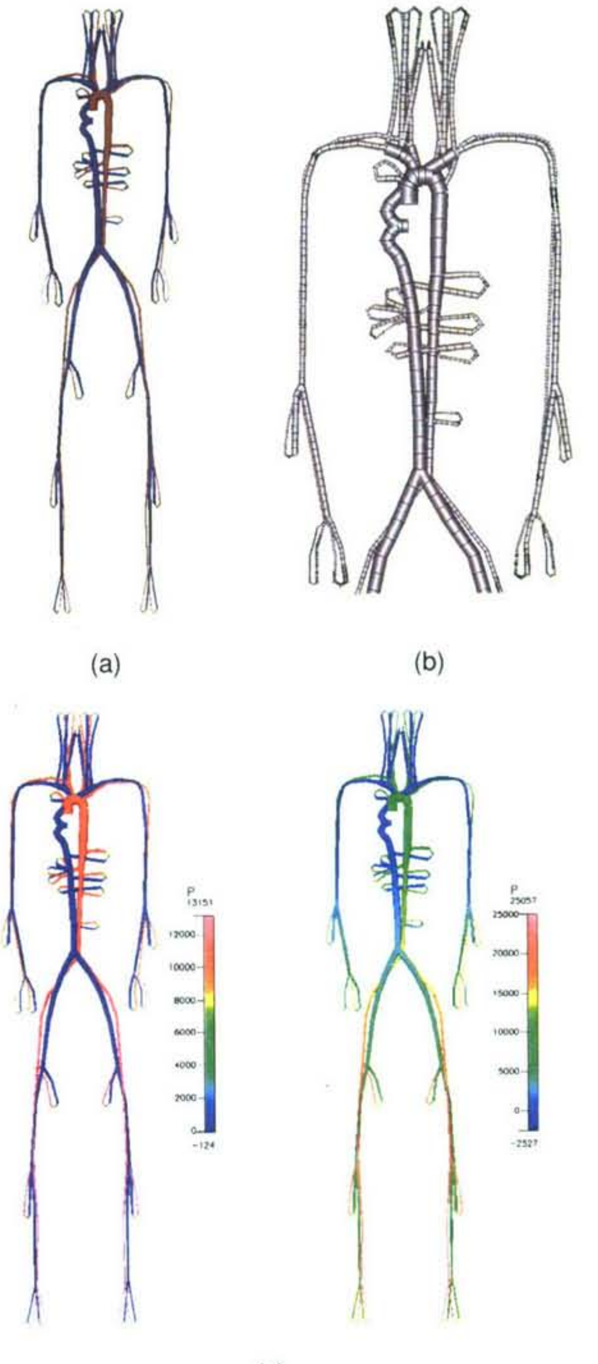


Figure 10. (a) Closed loop vasculature; (b) Zoomed in view of mesh; (c) Resulting pressure distribution without and with gravity turned on.

gravity resulted in pressure readings throughout the body, such as in the upper arm of approximately 120/80 mmHg. The baseline skeleton and vascular networks were generated in the Virtual Body software by morphing the previously generated standing soldier vasculature. Figure 11 illustrates the sitting soldier vasculature (11a), generated mesh (11b), and resulting pressure distribution for a given instant in time without (11c) and with (11d) gravity activated for the transient simulations.

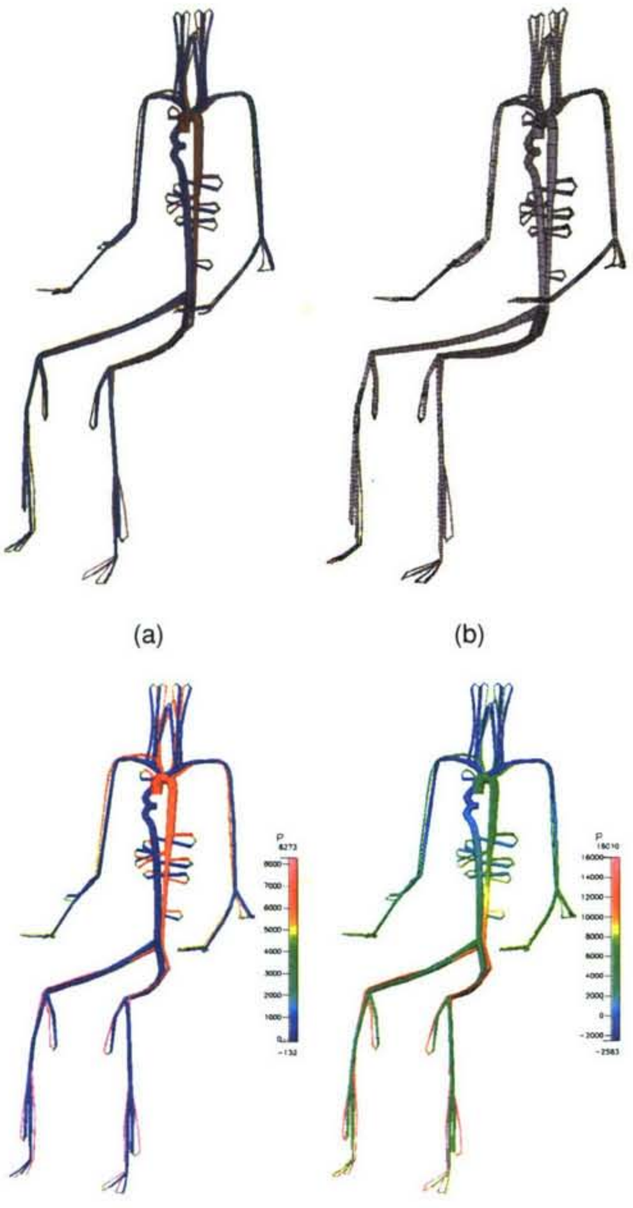


Figure 11. (a) Closed loop vasculature of sitting soldier, (b) generated mesh, and pressure distribution (c) without and (d) with gravity turned on for a given instant in time of transient simulation.

Experimental sled acceleration data taken from the BDB database, case number HIA0921, is plotted in Figure 12 along with the applied acceleration data for the simulation. The acceleration was applied after 15 seconds to allow the simulation to settle to a cycle independent solution. Also in Figure 12 can be seen pressure traces taken from various locations in the vascular network with gravity. Note that the applied acceleration occurs between 15 and 15.1 seconds. The pressure traces show several heart beats before and after the acceleration event (at time equal 15 seconds). Note when the acceleration occurs, the resulting pressure traces are dramatically altered with even such a short acceleration event (100 milliseconds). The pressure traces regain their repeatable behavior within approximately two heartbeats. This quick recovery can primarily be attributed to the fact only physical flow is being modeled, with no biochemistry. Biochemical reactions to such an event would release vasoconstrictors, adrenaline, endorphins, etc. which would most likely cause the repercussions of the event on the circulatory flow system to be felt for a longer amount of time, affecting the heart rate and vasculature tone. Future such simulations with metabolic reaction will be conducted in the near future.

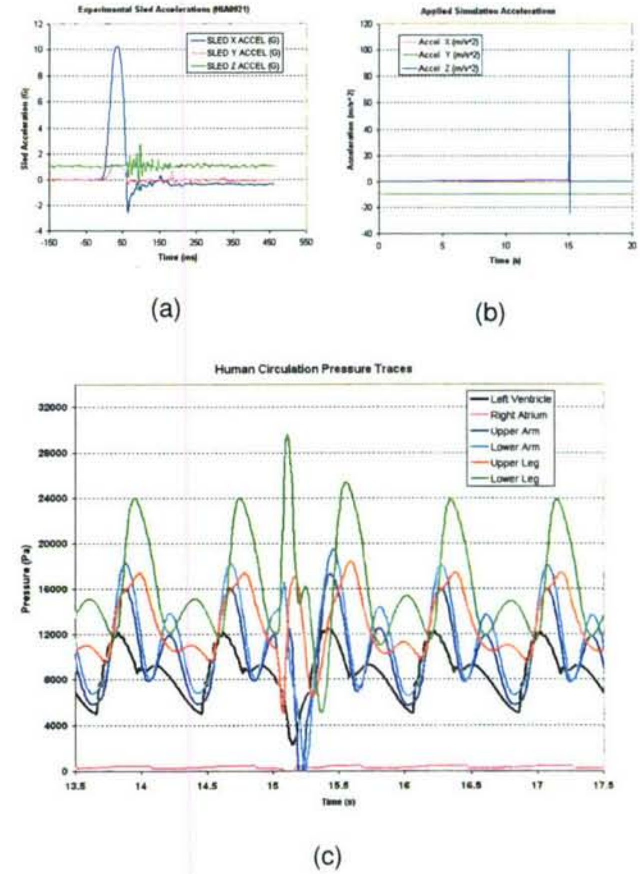


Figure 12. (a) BDB Sled acceleration experimental data. (b) Applied acceleration data. (c) Various pressure traces from different locations in the vasculature of the sitting soldier circulation with gravity and applied acceleration.

CONCLUSION

CFDRC's developed 3D Java based Virtual Body software framework allows a user to generate and manipulate anatomical systems of a virtual body in a user friendly environment. With the advances and availability of anatomical data from medical imagery and available databases, such a tool will be useful to researchers in integrating various detailed anatomical systems into a single environment. The linked/mapped framework between the baseline skeleton framework and generated anatomical systems allows for the morphing of the entire geometry through simple morphing of the baseline skeleton framework alone.

Future integration and enhancements of additional anatomical systems and components will further enhance the capabilities of the Virtual Body software framework. And finally, the Virtual Body's integrated capability to work with simulation packages, such as CFDRC's CoBi (flow, heat transfer, FEM, biochemistry) and other solvers in the near future, allow for fully integrated body geometry generation/editing and simulation analysis. The capabilities of the Virtual Body software presented in this paper represent just the starting point of the overall desired package and will be continually developed in the near future.

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